DESIGN FOR MEGAVOLT INVERSE-PINCH PLASMA SWITCH

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Abstract

To meet the requirements for the output switch of an ultra-high-power (>30 GW) pulser, an upgrading design for an inverse-pinch plasma switch (INPIS) is considered. The hold-off voltage of 1 MV is met by adopting multistage rim-fire electrodes and using SF_6 as the dielectric gas of the switch. The inductance and capacitance of the switch, which are restricted by the short rise-time (<0.1 μs) requirement, were met by adjusting the dimensions of the coaxial electodes of the switch. The input/output transmission lines attached to the switch will be immersed in oil to meet the high voltage insulation and impedence-matching requirements. Since the forwarding current is relatively low with respect to the switch capability, the lifetime of the switch is expected to exceed the requirement of 10^4 shots. The choice of the insulator and electrode materials is also discussed. Fabrication of the switch can be accomplished by well-established shop practices, and no special methods are required for its construction.

Introduction

The development of a compact, high-voltage, pulsed-power switch is essential for the compact pulser system development at the Electronics Technology and Devices Laboratory (ETDL) of the U.S. Army LABCOM. To provide the switching capability required for the compact pulser system, an upgrading design for an inverse-pinch switch (INPIS) is made using the experience gained with a prototype that was commutated by a hypocycloidal-pinch (HCP) plasma injection (plasma puff) trigger. The prototype INPIS was tested at NASA Langley Research Center for high-current and long-life use on spaceborne electric devices.

The ETDL's compact pulser requires that the final output switch should be able to transfer a train of 1-μs pulses with 36 kJ of energy at 1 MV and at the repetition rate of 10 Hz from the 2-ohm pulse-forming line (PFL) of the system. As analyzed by Burkes [1], these requirements can be met only by a spark gap near the upper limit of its performance, as shown in Figure 1. The proposed switch is a radically modified spark gap and outperforms the conventional spark gap, thus uniquely qualifying for adopting into the pulser. Furthermore, ETDL aims to achieve a six-fold reduction in weight and a two-fold reduction in volume of the pulser system. Therefore the switch must be compact and lightweight. However, these issues will not be treated here.

Principle

The proposed switch has a novel geometry in which an inverse-pinch mechanism is operative, and the pondermotive force, $\vec{F} = \vec{J} \times \vec{B}$, where $\vec{J}$ and $\vec{B}$ are the current density and magnetic induction, respectively, is activated to "disperse" and "move" the current sheet over the large area of the electrode surface instead of constricting the current into a filament and causing a hot spot formation as in conventional spark gaps [2].

Figure 2 shows the cross section of the proposed switch designed for high-voltage hold-off operation. The electrodes have a cylindrical configuration and are coaxially placed. Their concentric arrangement (inner electrode within the outer electrode) forms an annular

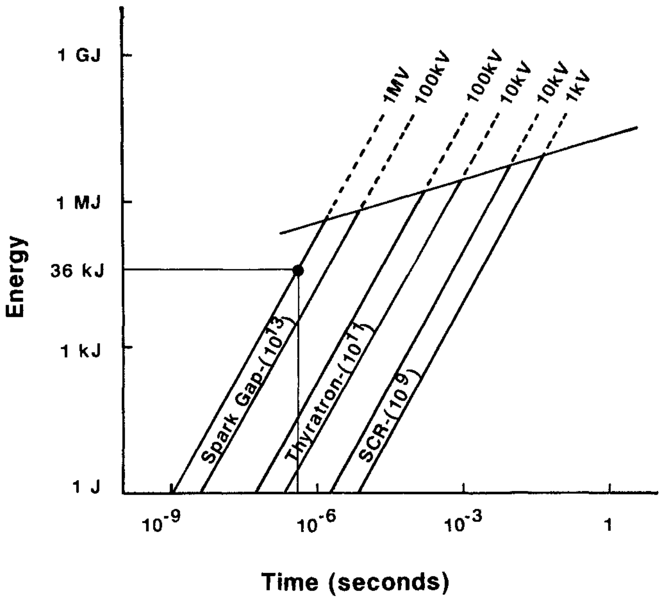

Fig. 1. Operating regions for various switches on the pulse energy vs duration diagram from Ref. 1.

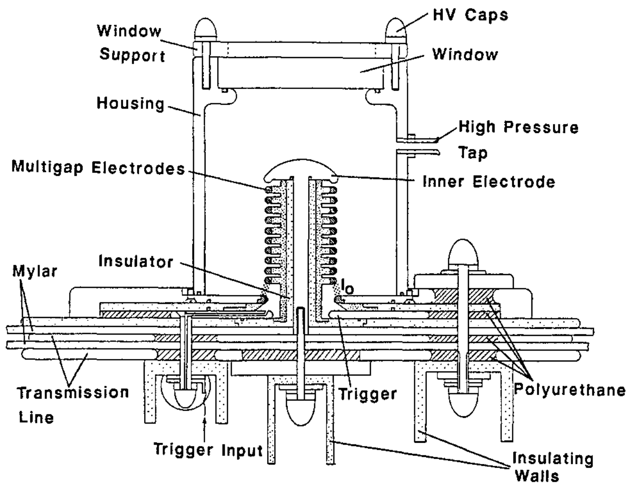

Fig. 2. Cross-section of the proposed high-voltage INPIS switch.

gap between the inner and outer electrodes. The inner electrode has a mushroom (or reentrant) shape, and its mushroom skirt consists of multiple ring electrodes spaced uniformly to form a series of gaps for high-voltage hold-off. This arrangement is similar to the rim-fire spark gap of Sandia Laboratory [3]. The inner electrode has a conducting column on the axis surrounded by a tubular insulator which is extended through the hollow center of the outer-electrode base and the plasma-puff trigger electrode. The annular opening, which is formed between the insulator surrounding the inner electrode and the base of the outer electrode, is used for the plasma injection from the HCP trigger.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 1989**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Design For Megavolt Inverse-Pinch Plasma Switch**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Tetra Corporation 4905 Hawkins, N.E. Albuquerque, NM 87109**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT
To meet the requirements for the output switch of an ultra-high-power ()30 GW) pulser, an upgrading design for an inverse-pinch plasma switch (INPIS) is considered. The hold-off voltage of 1 MV is met by adopting multistage rim-fire electrodes and using SF6 as the dielectric gas of the switch. The inductance and capacitance of the switch, which are restricted by the short rise-time (<0.1 ~s) requirement, were met by adjusting the dimensions of the coaxial electodes of the switch. The input/output transmission lines attached to the switch will be immersed in oil to meet the high voltage insulation and impedence-matching requirements. Since the forwarding current is relatively low with respect to the switch capability, the lifetime of the switch is expected to exceed the requirement of 104 shots. The choice of the insulator and electrode materials is also discussed. Fabrication of the switch can be accomplished by well-established shop practices, and no special methods are required for its construction.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

The trigger electrode and the base of the outer electrode form a planar (i.e., HCP) chamber in which a plasma ring is generated and launched radially. When the high-voltage pulse is fed into the HCP trigger electrode, electric flashover occurs over the ceramic disk insulator, and the resulting plasma sheet moves radially inward toward the axis of the switch. It then puffs up axially toward the tip of the lowest ring of the inner electrode, thus initiating the breakdown currents (I_o in Fig. 2) in the gap between the inner and outer electrodes. The annular gaps in series between the ring electrodes also break down simultaneously due to over voltage caused by the lowest-gap closing.

After breakdown, the current sheet (I_p in Fig. 2) is immediately dispersed out in a radial direction and then axially sweeps over a wide area of the electrodes until the currents cease to flow. The motion of the current sheet is the result of the inverse-pinch mechanism working on the plasma and a snow-plow model may be used for simulation of its dynamics. The current-sheet velocity is known to depend on the gas density and electrical input parameters [4-8].

The load coupling to the switch is made by a flat plate transmission line at the base of the switch. The transmission lines of the compact pulser are required to have an impedance of 2 ohms, which will be met by oil-immersed, flat plate lines.

Design Concepts

The key factor in designing the proposed switch for the ETDL's compact pulser is to hold off a high voltage up to 1 MV. The compact pulser, when fully developed, will consist of a 1-MV prime power supply, a pulse-forming line with 2-ohm impedance, and an output switch capable of delivering a pulse train of 36 kJ per 1-μs pulse with a rise time <1 μs. The required repetition rate in burst mode is 10 Hz. This design study addresses how to meet these requirements.

Voltage Hold-Off

The increase of the switch hold-off voltage to the level required by the pulser (i.e., up to 1 MV) is a very significant task. In general the high voltage hold-off may be attained by the use of the high- or low-pressure side of the Paschen curve (see Fig. 3), i.e., by adjusting the gap distance of electrodes, by adopting the multigap electrode, by using high-pressure electronegative gases, or by combinations of these options. Also, it may be achieved by a series of multiple switches with lower voltage hold-off, but this method is less desirable because of the increase in impedance and inductance. The megavolt hold-off in an air gap can be made under a high pressure of a few atmospheres or at a low vacuum pressure down to 1-mTorr level. The gap distance between the inner and outer electrodes may be adjusted according to the pd (pressure•distance) value on the Paschen curve for the given gas breakdown voltage. The selection of the type of gas and the pressure may be made in addition to adjusting the gap. Various types of electronegative gases (e.g., SF_6) are available.

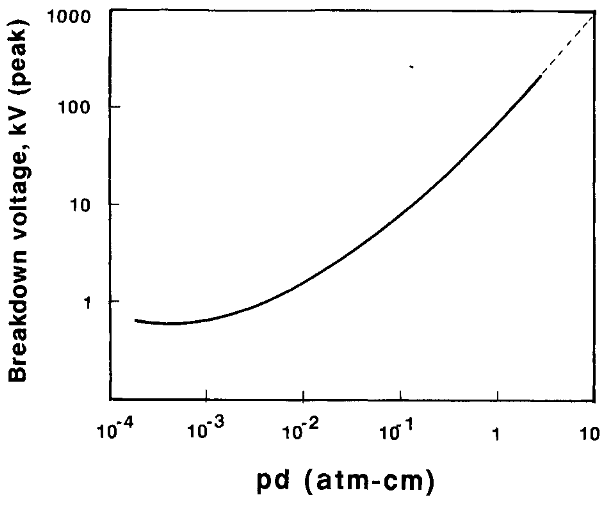

Fig. 3. Paschen curve for nitrogen.

A disadvantage of the low-pressure operation is a significant change of the switch inductance due to increasing arc-runner distance during the dynamic period of the INPIS switch. Figure 4 illustrates that the hold-off voltage of the switch above 1 MV is feasible both at high-pressure (of N_2) and low-pressure (of H_2) sides of the Paschen curve. Figure 5 is the same for SF_6 [9].

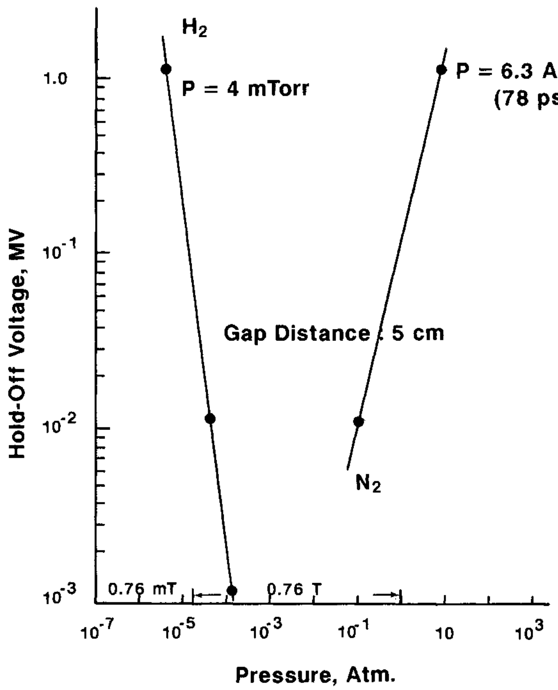

Fig. 4. Breakdown voltage vs gas pressure for the gap distance of 5 cm.

For the proposed switch, the first choice is SF_6 which has pd = 10 atm-cm for 1-MV breakdown in a uniform field [9]. The required pressure p is therefore $p \geqslant 1.7$ atm for the gap with d = 6 cm. However, at high pressures, Paschen's law fails, and an increase in pressure at a constant gap distance results in saturation in the breakdown voltage, as shown in Fig. 5 (taken from Ref. 9).

For a 4-atm pressure, a 6.5-cm gap is necessary for a 1-MV hold-off. Furthermore, the field distribution depends on the geometry and materials used for the gap, and the breakdown voltage in the INPIS may even be lower for the above conditions. Because of these uncertainties, a preliminary test on hold-off voltage of the INPIS is necessary before finalizing the design of the 1-MV INPIS. The gap distance of 6.5 cm can be formed by placing the lowest gap of 1 cm and 11 gaps of 0.5 cm between ring electrodes in series. This

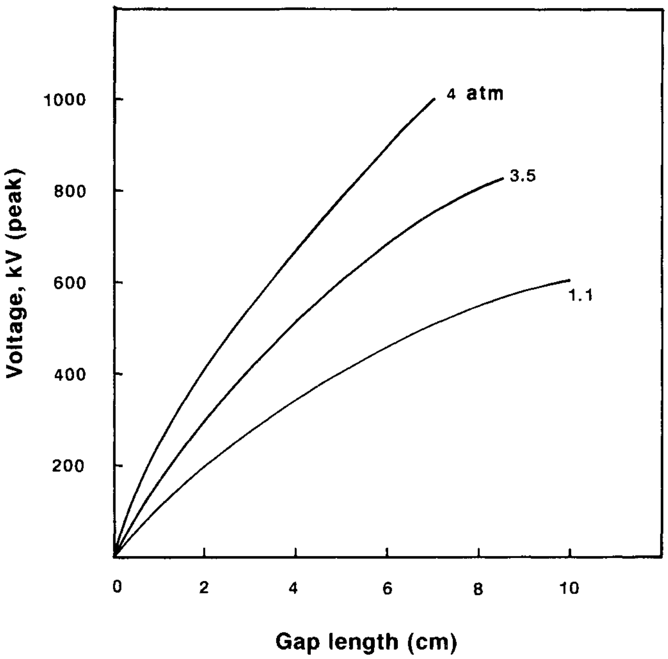

Fig. 5. Breakdown voltage vs gap length for different SF_6 pressures (from Ref. 9).

arrangement will ensure easy triggering by a plasma puff or some other trigger method.

The multiple electrode-ring arrangement of the inner electrode is supported by grooved insulator spacings.

The breakdown over the surfaces of these spacings has to be considered. It is known that the surface breakdown voltage does not increase proportionately with SF_6 gas pressure [8]. Figure 6 shows the insulating spacer efficiency, the ratio of the breakdown voltage over the spacer to that of the gas gap with the same distance, vs SF_6 pressure. For SF_6 pressure of 4 atm, the efficiency is 0.5. To obtain the hold-off voltage

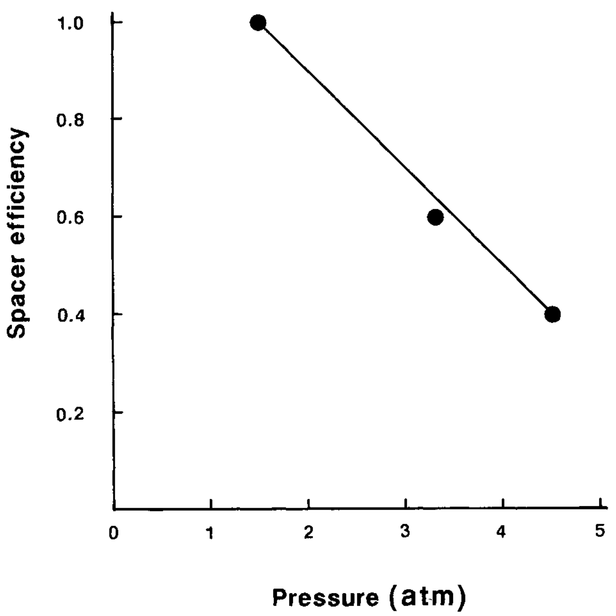

Fig. 6. Spacer efficiency vs SF_6 pressure from Ref. 9.

desired, the spacer must have a distance twice that of the gas gap.

To take this effect into account, the plasma switch design (Fig. 7) has the ratio of the insulator surface distance to the gas gap equal to 15.8 mm/5 mm or 3.2. The breakdown voltage over the insulator is thus 1.6 (=3.2 × 0.5) times that of the gas gap, thus insuring the voltage hold off over the surface. Detailed geometry of the ring electrode/spacer unit is shown in Fig. 7.

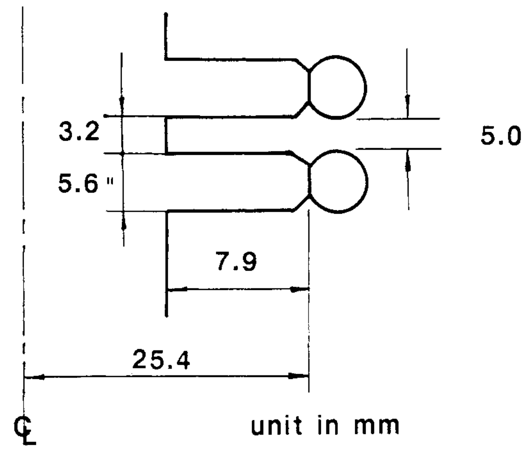

Fig. 7. Ring electrode/spacer arrangement.

Current Capability

The current forwarding capability of the switch is easily estimated by the previous test results. For instance, a peak current of 283 kA in 10-μs pulses used for previous tests occurred without detectable wear for over 6,000 shots [4]. The current for the 36-kJ pulse with a 1-μs pulse width is only 36 kA. The effective electrode surface of the 1-MV switch is equal to that of the ones tested. Therefore, the switch will exceed the requirement. The charge transfer capability of the switch is at least an order of magnitude above the requirement.

Rise Time

The rise time of the proposed inverse-pinch switch is inherently shorter than that of the trigatron switch because of its very low inductance. Table I shows the inductance of the proposed switch as compared to that of a typical spark gap. The test result of a similar switch had the rise time of 0.31 μs. However, this rise time was attributable mainly to the inductances of external components such as transmission cables and interfaces, rather than the switch inductance. The proposed switch will be coupled with a low-impedence, flat-plate transmission line (2 ohms) rather than the multiple-cable hookup used for the prototype. This coupling will result in a rise time <<1 μs. The inductance is also dependent on the plasma dynamics during switching action and can be determined by the current sheet position in time. However, this inductance is calculated to be negligibly small. The rise time t_r of the switch alone is approximated by $t_r = 0.75 \sqrt{LC}$.

Table I

	Spark Gap	INPIS
Inner current dia., mm	2	15
Return current dia., mm	200	55
Inductance, nH/m	920	360

The geometry in Fig. 2 has $L \simeq 55$ nH and $C = 2.5$ nF, $LC \leqslant 137.5 \times 10^{-18}\ s^2$; therefore, $t_r = 8.8$ ns. The impedence of the switch $Z_{SW} = (L/C)^{1/2} = 4.7$ ohms. The output pulse-shape distortion due to the impedance mismatch between the 2-ohm transmission line and the switch may be tolerated.

Materials

A number of electrode materials such as thoriated tungsten and copper-tungsten alloy for high-current-density operation are in use for spark gaps. Also there are a few proprietary materials developed for prolonging useful life of power relay terminals or flashlamp electrodes. These special electrode materials can withstand 10-100 times higher current densities than usual materials such as brass, copper, or aluminum. For tests of the high-voltage switch, we chose molybdenum as the material for the electrode tip to be welded to the brass electrodes because a relatively low current density is estimated for the hollow electrode tips in the INPIS switch. The tungsten alloys are reserved for the full-scale switches in the later phase of the project. Molybdenum has several advantages over usual materials because of its high melting point (2620°C), low resistivity ($\eta_{Mo} = 5.7 \times 10^{-6}$ ohm-cm vs $\eta_W = 5.1 \times 10^{-6}$ ohm-cm), and low work function ($e_{Mo} = 4.3$ eV vs $e_W = 4.5$ eV). Molybdenum is softer and more ductile than tungsten and can easily be shaped in complex forms with ordinary shop machines, while tungsten and its alloys are more difficult and more expensive to shape in special geometries.

The choice of the insulator material significantly influences the switch life. It is not uncommon that spark-gap switch life is terminated by the damage of the insulator rather than the electrode. The INPIS has a tubular insulator about the axis that is subject to heat and uv irradiation and shock wave hammering. Therefore, the selection of the insulator material is of utmost importance.

Various plastics are commonly used in spark-gap switches for high insulating strength and ease of fabrication. However, all plastics are ruled out for the INPIS because of their low melting points. Therefore refractory materials are chosen for the INPIS.

Among various refractory materials, the most suitable for high-temperature high-stress applications are those of alumina ($A\ell_2O_3$), zirconia (Zr_2O_3, M.P. = 2593°C), and their derivatives. For the first phase testing, alumina is chosen for its commercial availability, and zirconia will be tested in the later phase.

Lifetime

The useful life of the switch can be estimated based on the measured wear rates of electrodes expressed in units of μg/coulomb. The previous tests indicate less than 50 μg/coulomb for 6,000-coulomb transfer without appreciable local wear. The pulser requires a 36-kJ pulse energy at 1 MV or a charge transfer of 36×10^{-3} coulomb/pulse through the switch. Therefore, a shot life of $6000/0.036 = 1.6 \times 10^5$ shots is conservatively expected. The ETDL's requirement is only 10^4 shots and the switch will exceedingly outperform this requirement.

Summary

A design concept for upgrading an inverse-pinch plasma switch to meet the requirements of a 1-MV pulser has been developed. The hold-off voltage is obtained by adopting multistage rim-fire electrodes and using a N_2/SF_6 mixture as the working gas. The rise time (<1 μs) requirement is met by adjusting the dimensions of the coaxial electrodes and minimizing the switch inductance. The lifetime requirement is easily met by the switch's special coaxial geometry, which can be formed with specially chosen materials.

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